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Resistance Training to Momentary Muscular Failure Improves Cardiovascular Fitness in Humans: A Review of Acute Physiological Responses and Chronic Physiological Adaptations

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ABSTRACT

Steele J, Fisher J, McGuff D, Bruce-Low S, Smith D. Resistance Training to Momentary Muscular Failure Improves Cardiovascular Fitness in Humans: A Review of Acute Physiological Responses and Chronic Physiological Adaptations. **JEPonline** 2012;15(3):53-80. Research demonstrates resistance training produces significant improvement in cardiovascular fitness (VO_2 max, economy of movement). To date no review article has considered the underlying physiological mechanisms that might support such improvements. This article is a comprehensive, systematic narrative review of the literature surrounding the area of resistance training, cardiovascular fitness and the acute responses and chronic adaptations it produces. The primary concern with existing research is the lack of clarity and inappropriate quantification of resistance training intensity. Thus, an important consideration of this review is the effect of intensity. The acute metabolic and molecular responses to resistance training to momentary muscular failure do not differ from that of traditional endurance training. Myocardial function appears to be maintained, perhaps enhanced, in acute response to high intensity resistance training, and contraction intensity appears to mediate the acute vascular response to resistance training. The results of chronic physiological adaptations demonstrate that resistance training to momentary muscular failure produces a number of physiological adaptations, which may facilitate the observed improvements in cardiovascular fitness. The adaptations may include an increase in mitochondrial enzymes, mitochondrial proliferation, phenotypic

conversion from type IIx towards type IIa muscle fibers, and vascular remodeling (including capillarization). Resistance training to momentary muscular failure causes sufficient acute stimuli to produce chronic physiological adaptations that enhance cardiovascular fitness. This review appears to be the first to present this conclusion and, therefore, it may help stimulate a changing paradigm addressing the misnomer of ‘cardiovascular’ exercise as being determined by modality.

Key Words: Aerobic, Metabolic, Molecular, Myocardial

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1. INTRODUCTION

1.1 Resistance Training and Cardiovascular Fitness Measures

Previous review articles have examined the effects of free weights, variable resistance machines, hydraulic resistance machines, pneumatic resistance machines on cardiovascular fitness (80,144). To understand the role of resistance training (RT) in cardiovascular fitness (CV), it is important to identify the variables involved. Midgley et al. (101) indicate that the variables of CV fitness are maximum oxygen consumption ($\text{VO}_2 \text{ max}$), economy of movement, and lactate threshold (Tlac). The opinion that RT must be supplemented with some form of aerobic or endurance training (such as running or cycling) in order to improve CV fitness is widely accepted, which presents a dichotomy between the two training modalities. Reviews looking at the effects of RT on the CV variables have concluded that although RT can improve such variables, it is not as effective as traditional aerobic training or concurrent training (80,144). However, methodological issues result in a certain degree of difficulty in the interpretation. The result is that such conclusive statements are questionable. The

most prevalent methodological issue is that of an inappropriate definition and control of RT intensity. We have recently discussed (48) definitions of intensity along with concerns about the use of percentage of one repetition maximum (1RM), which refers to *load* to falsely represent intensity. Intensity is actually representative of effort, not load, and as such only one accurate measure is possible during RT; that of 100%, that is, when the participant reaches maximal effort or momentary muscular failure (used interchangeably with 'failure' within this review). Consideration of this important factor leads to an entirely different conclusion than previously published (80,144).

Where studies have appropriately controlled for intensity (as defined in this way), by having participants perform RT to momentary muscular failure, the results indicate improvements in both predicted VO_2 max (112,130) and measured VO_2 max in both young (69,99) and older adults (67). Research comparing RT conducted to failure, as previously recommended (48), with aerobic training suggests that the two modalities do not differ in the degree of VO_2 max adaptations produced (67,99). However, when performed to failure, one study reported that RT does not significantly improve VO_2 max (55). Unfortunately, the authors did not report the within groups comparisons and only reported between group comparisons for post-training data between controls and training groups. This means they did not account for difference in the groups' starting fitness (which did differ, though it is also uncertain whether this was significant) at the start of the study. This may have influenced the degree of improvement from training. Indeed, both the RT group and the aerobic treadmill group improved VO_2 max. But, due to the lack of within group comparison, it is not certain whether the changes were meaningful in the RT group. Reviews have commented on the lack of evidence to support the use of RT to improve VO_2 in trained athletes (80,144). However, most research suggests that such a population is unlikely to produce meaningful improvements in this variable regardless of training modality due to their level of trainability (76).

A further potential adaptation is that of running economy (RE), which considers oxygen cost at a given absolute exercise intensity. For example, if two individuals were to perform exercise at the same absolute exercise workload, the person with the lower VO_2 would be considered the more economical. Much of the research on the effect of RT on RE indicates that the researchers have not controlled the RT variables, including intensity (114,129). Also, the use of periodized programs renders it impossible to determine which variables are causing the observed effects (45). However, studies in which RT has been performed to failure with athletic populations have reported significant improvement in economy compared to the control groups that continued to perform the usual aerobic training program (75,102,141). A further study examining the effect of RT to failure upon economy in untrained older adults reported significant improvement in 2 of the 3 functional tasks with a significant decrease in respiratory exchange ratio. This finding indicates an increased utilization of oxidative metabolism (62).

Other markers of CV performance are lactate threshold (Tlac) and submaximal lactate concentration. Both markers have been shown to improve in untrained subjects as a result of RT (98). But, in trained athletes, Bishop and colleagues (19) reported no significant changes in Tlac or VO_2 . However, as with VO_2 , Tlac is unlikely to improve significantly in trained athletes (76). More research is required within this area, appropriately controlling for RT variables, particularly intensity, and considering differing populations (i.e., untrained and sedentary).

Studies have examined both the traditional approach to RT, involving rest periods ranging from 1 to 3 min between sets and exercises (62,67,112,130,141) and circuit based training, where the participant moves quickly with minimal rest between exercises (2,99,116) with improvement in CV. In addition, these studies demonstrate considerable variation in the control of other variables such as load, volume, and frequency. Yet, the consistency among all the studies is that they all had the subjects to

perform RT to failure resulting in a significant improvement in the CV fitness variables. It would appear that the most important variable with regards to producing improvement in CV fitness via RT is intensity. O'Hara et al. (111) provide an interesting review of this point with emphasis on leg RT. They concluded that intense RT (i.e., to failure) induces marked improvement in nearly all variables associated with aerobic capacity.

In summary, despite research being inconclusive with regards to the effect of RT on Tlac, it appears to support the recommendation that RT (whether circuit style or traditional, and independently of other RT variables) performed to failure is sufficient to induce significant improvement in CV fitness. Maximum oxygen consumption and RE improvements may be comparable to traditional endurance training. Additionally, and in corroboration with the findings that RT to failure can produce improvements in measures of CV fitness, studies also report significant improvement in aerobic endurance time to fatigue (2,69,116,141) and velocity at VO_2 max (102).

Other modes of exercise performed at a high level of intensity have also produced an improvement in CV fitness. For example, intense cycle interval training of $\sim 1.5 \text{ hrs} \cdot \text{wk}^{-1}$ has been shown to produce similar CV adaptations and increased endurance when compared to traditional endurance training of $\sim 5.5 \text{ hrs} \cdot \text{wk}^{-1}$ (27,53,66,88). Since duration appears to be a less significant factor versus intensity in causing improvement in fitness through this modality, it is important to consider the relevance of modality and the relative merits of RT (notably shorter in duration and generally higher in intensity). The general dichotomy drawn between RT and traditional aerobic or endurance training would appear unfounded. In fact, it is reasonable to conclude that modality appears to be of little relevance in producing an improvement in CV fitness since the evidenced indicates that improvement is possible by RT as long as intensity is high.

The purpose of this review is to present the findings of a literature search suggesting that the dichotomy between RT and traditional aerobic or endurance training is not as clear as believed. There are important practical implications from this review, particularly for those who wish to engage in training to improve CV fitness. The review will comprise two main sections. First, the acute physiological responses to RT research that might stimulate chronic adaptations to enhance CV fitness will be examined. Secondly, this review will present the research that investigated the effects of RT on the chronic physiological adaptations, as well as considering the mechanisms of RT that might be responsible for stimulating the adaptations.

2. METHODS

2.1 Literature Search

A literature search was completed prior to the writing of this review between March 2010 and January 2011 using MEDLINE/Pubmed, SportDiscus databases, and Google Scholar search engine using a plethora of key terms associated with RT, CV fitness, and physiological variables/processes (e.g., 'RT and CV', 'RT and endurance', 'RT and aerobic', 'RT and VO_2 ', 'RT and economy', 'RT and lactate threshold', 'RT and metabolic', 'RT and molecular', 'RT and myocardial', 'RT and vascular' as well as other associated synonyms, similar terms, and combinations). Resistance training appreciably covers a wide range of types of resistance, and it is acknowledged that in fact all movement occurs against resistance both internal and external. However, the style of exercise performance irrespective of the resistance types appears to be of key importance (48) and thus, within this review, RT as an exercise modality was considered as exercise utilizing any of the following typical resistance types: free weights (including bodyweight exercise performed in the same characteristic manner), variable resistance machines, hydraulic resistance machines, and pneumatic resistance machines. Studies that described training as 'high-resistance' but, however, was performed on a cycle ergometer were

not considered to be RT. Instead, they were considered as traditional endurance modalities. Initially, the inclusion and exclusion criteria focused on methodologies that comprised randomized controlled studies that examined acute responses to a RT stimulus, as well as controlled training intervention studies that examined physiological phenomena in response to RT. However, as the number of articles initially excluded grew, it was necessary to re-evaluate the process. It became apparent that much of the literature contained numerous methodological inconsistencies that rendered concise interpretation difficult and that are heavily documented within the present article. As a result, it was decided to take the approach of a systematic narrative review, which employed specific search and inclusion methods but did not specify methods for the critical appraisal of the studies included. This allowed for a holistic interpretation of the wide ranging and myriad research identified. It also allowed for the benefits of both types of review to be employed (36). We limited our inclusion criteria to research involving healthy, untrained and athletic populations that examined: (a) acute variables that were considered to be involved in the improvement of CV fitness in response to RT; (b) measures of CV fitness in response to an RT intervention (e.g., VO_2 max, endurance time to fatigue, lactate threshold, and economy of movement); and (c) the adaptation in physiological variables that were considered to contribute to an improvement in CV fitness (and highlighted under methodological considerations) in response to RT.

2.2 Methodological Considerations and Research Interpretations

As highlighted earlier, the definition and control of intensity were considered important to the interpretation of the results. Hence, when studies controlled for both while performing RT to failure, it was noted. In regards to studies that did not define or control for intensity but had the participants perform RT to a high degree of intensity with potentially important findings, a reasonable interpretation of the intensity of the RT is offered. Although this was based on knowledge of typical maximum repetition ranges at particular relative loads (70,133), the limitation of quantifying the findings based upon our own definition is acknowledged. It is suggested that in future research both the definition and intensity are appropriately stated so that a clearer interpretation of the findings is possible.

In determining the acute responses and the chronic adaptations to examine, it was clear that much incongruity existed regarding the most important factors involved with determining endurance performance and CV fitness measures (15,16,106,107,108,123). Since it was not the purpose of this review to discuss the validity of one hypothesis over another, selected areas of adaptation that are considered to have merit in the improvement of CV endurance were examined. They are: (a) CV (i.e., myocardial morphology and vascular morphology); (b) metabolic (i.e., oxidative enzymes); and (c) molecular (i.e., muscle fiber composition and mitochondrial density). The acute responses that might be considered important in stimulating the adaptations to CV improvement (i.e., oxygen cost, blood pressure, heart rate, volume of blood pumped, and vascular responses), metabolic (i.e., anaerobic metabolic activity, aerobic metabolic activity, and blood lactate), and molecular (i.e., molecular signaling pathways) were examined. Chronic adaptations have been presented under CV adaptations involving the oxygen transport system (i.e., myocardial and vascular adaptations), and metabolic and molecular adaptations at the local muscular level (including enzymatic, muscle fiber phenotype, and mitochondrial adaptations). Corresponding acute stimuli have also been presented as determined by these distinctions.

In drawing conclusions, the 'weight of available evidence' approach was used to provide a holistic interpretation of the research and propose hypotheses of physiologically plausible mechanisms to explain the effect of RT to failure on the CV fitness variables.

3. PART 1: ACUTE RESPONSES TO RT

3.1 Oxygen Cost Responses

To stimulate improvement in CV endurance, untrained subjects and trained subjects should work at ~50% and ~70 to 80%, respectively, of VO_2 max (9). Thus, the question is: “Would this thinking apply as well to RT?” It might be presumed that since RT to failure produces significant improvement in CV fitness measures, it must present a significant VO_2 response as well. It is of interest then to examine whether this may be an acute stimulus during RT that potentially stimulates improved CV fitness. Unfortunately, when examining the VO_2 of RT, many studies have failed to either to control intensity or failed to define it sufficiently (18,56,124). As a result, it is questionable whether the findings accurately represent the VO_2 response during RT to failure. Other studies have performed RT to a point of failure, but the data were recorded as an average across the duration of a session, including rest periods, whereby only a small fraction of time was actually spent performing RT (~6.21 to 8 min exercise out of 24 to 30 min measured (20,117,118). Indeed, Phillips and Ziuraitis (117,118) reported a moderate intensity of RT based on metabolic equivalents (METs) of 3 to 6 for the RT sessions, despite subjects performing exercise to failure (i.e., maximal intensity). The VO_2 and other CV variables may have been significantly underreported when averaged. Rating of perceived exertion (RPE) is reported to be significantly lower when the data are averaged to include rest periods (143) in the same manner as the aforementioned VO_2 studies. This further suggests the potential that the VO_2 response recorded in these studies may not have accurately reflected the intensity of RT.

It has also been demonstrated that the VO_2 of a particular exercise is dependent on the active muscle mass (9,142), which should be considered when measuring VO_2 in RT studies. Most studies have reported that the average VO_2 during RT is less than 50% of maximal whole body capacity (17,20,28,35,43,74,117,118). Hence, in light of the recommendations for achieving particular levels of VO_2 for CV improvement, the average VO_2 during RT data led Jung (80) to conclude that the VO_2 of RT is “...hardly a substantial stimulus for improving aerobic capacity in all but the most sedentary of people.” However, the research by Strømme et al. (142) and the data compiled by Åstrand et al. (9), suggests that VO_2 during RT should be relatively low compared to larger muscle mass exercise such as treadmill running or cross country skiing (especially if it is measured for a specific exercise in isolation). Perhaps, when considering VO_2 during RT, it should be analyzed relative to the maximal attained VO_2 during RT as opposed to the maximum whole body VO_2 during larger muscle mass exercise.

Despite the difficulties in determining VO_2 during intense RT, it is reasonable to expect that as RT intensity is increased a concomitant increase in VO_2 occurs. In fact, Gotshalk et al. (56) showed that during a circuit weight session where load and repetition were held constant across the number of circuits completed, VO_2 increased with each circuit presumably as the subjects experienced fatigue. As the degree of effort increased, the intensity of the exercise performed increased. It has also been suggested that longer repetition durations may be relatively higher in intensity than shorter durations (25). Therefore, it is again reasonable to expect that a greater intensity elicited by longer duration repetitions result in a greater VO_2 response. Barreto et al. (14) reported no difference in VO_2 values in longer duration repetition (2 sec concentric and 2 sec eccentric phases) circuit exercise compared to a shorter duration (1 sec concentric and 1 sec eccentric phases). However, they also commented that the difference in repetition durations may not have been sufficient to demonstrate a significant difference in VO_2 . Hunter et al. (73) attempted to compare superslow (SS) training (10 sec concentric, 5 sec eccentric) with traditional style RT (TT). No restriction on duration was instructed for TT (average concentric duration was 0.9 sec and average eccentric was 0.8 sec). Initially, their results suggested that TT elicited a greater increase in VO_2 than SS. However, the TT group trained with a significantly greater load (65% 1RM) than the SS group (25% 1RM) for an identical period of time, suggesting that the TT group may have trained at a higher intensity (i.e., closer to failure).

It is not clear from current research what the true VO_2 response is from RT to failure. This is primarily due to methodological issues such as averaging VO_2 across RT sessions and, then, comparing it to the whole body VO_2 measured via larger muscle mass exercise. Increasing intensity with RT may increase the VO_2 response, which might hypothetically include increasing repetition duration. However, due to perhaps the insufficient differences in duration between protocols and inadequate control of intensity, this is not demonstrated in the published research. Future studies should use research designs that allow for examining the hypothesis that longer repetition duration results in a greater VO_2 response due to a higher intensity (i.e., by keeping the load and set duration constant and only varying repetition duration between conditions). Then, too, why not use a research design that controls for the RT intensity and record acute VO_2 during RT and not average it across sessions that include rest? This would help clarify whether the VO_2 response during RT is an important stimulus for CV fitness adaptations. Indeed, a common misconception is that a high percentage of whole body VO_2 max is required for improvement of aerobic capacity. In fact, a review of the literature has shown that there is no substantial evidence to suggest that a defined percentage of whole body VO_2 max during a typical endurance training program is necessary for its improvement (101). Training status of the active muscles has also influenced the measurement of VO_2 (68,142), which indicates an adaptation at the muscular level independent of whole body VO_2 obtained during endurance exercise. This suggests that considering VO_2 during training measured relative to VO_2 max obtained through large muscle mass exercise as an indicator of its efficacy in improving CV fitness may be of little value.

3.2 Metabolic Responses

It is well-known that aerobic training is different from anaerobic training. The first is considered synonymous with CV or traditional endurance training while the second is synonymous with strength training or high intensity endurance training (154). However, there is the very real likelihood that the distinction between the two terms is an oversimplification where such a distinct dichotomy does not in fact exist. The definitions imply that anaerobic training is an insufficient stimulus to improve aerobic metabolism. Indeed, many researchers conclude that RT is not the appropriate stimulus to improve aerobic metabolism (17,20,28,35,43,74,80,117,118,143). This conclusion appears to be due to the traditionally taught concepts about each type of training. But, what if the thinking is an unfounded misconception in that the energy producing metabolic pathways involved in muscular contraction may differ with exercise modality (37) rather than instead intensity? Metabolically, RT should stimulate the aerobic system.

Although the concept of 'aerobics' was popularized by Cooper (37) to encourage the isolated use of the aerobic pathways to produced improvement in CV endurance, the powerhouse of the cells (mitochondria) are fueled by pyruvate produced by a series of chemical steps that do not require oxygen (glycolysis). This means that anaerobic metabolism and aerobic metabolism are metabolically linked (127). Yet, aerobic glycolysis (meaning, the use of pyruvate by the Krebs's Cycle when there is adequate oxygen to support its link with the electron transports system) is very likely stimulated via intense anaerobic work independent of modality. In agreement, numerous studies have demonstrated improvement in aerobic capacity following intense interval training (27,53,66,88). Similar adaptations are likely to occur via RT to failure, and as such suggest that modality of exercise is irrelevant to the stimulation of aerobic metabolic pathways.

The effect of intensity is especially important in the discussion of RT resulting in aerobic adaptations. Increasing exercise intensity causes an increase in motor unit recruitment up to its regulated maximum, which is independent of exercise modality (30,83,110). Also, presumably, pyruvate dehydrogenase is maximally active at maximal exercise intensity. This is important because it is the

rate-limiting enzyme responsible for entry of pyruvate into the mitochondria (135). Mayer and colleagues (92) demonstrated that during maximal exercise, infusion of dichloroacetate, a metabolic stimulator of pyruvate dehydrogenase resulted in an increase in VO_2 . Other research has applied intra-arterial infusion of adenosine to induce a vasodilatory response to the quadriceps muscles while performing maximal one-legged knee extension exercise (13) and a maximal cycle ergometry test (29) in order to induce enhanced O_2 delivery, yet found no increase in muscle or whole body VO_2 . This supports the concept that muscular work of maximal intensity, independent of modality, may already result in maximal rates of aerobic metabolism at the local active musculature as determined by the rate of pyruvate entry into the mitochondria by pyruvate dehydrogenase. This is demonstrated by the finding that oxygen supply is apparently adequate to match the intensity. Therefore, applied to RT (13), this suggests that training to failure also elicits the greatest acute activity of both anaerobic and aerobic glycolysis in the local active musculature, and that such training is presumably a sufficient stimulus for aerobic energy (43) and adaptation.

3.3 Blood Lactate Responses

A discussion of metabolic responses to RT includes the topic of blood lactate (Blac) due to its potentially deleterious effects on muscle contraction and endurance at high concentrations through subsequent metabolic acidosis (77,154). It has been suggested that greater oxidative enzyme activity from endurance training leads to an augmented rate of pyruvate entry to the mitochondria and less mass action of lactate dehydrogenase (77). However, as explained previously, the enzyme pyruvate dehydrogenase responsible for pyruvate's transport to the mitochondria is rate-limiting (135). Any adaptation in Blac from RT then is more likely due to a stimulation, and increased expression, of monocarboxylate transporters that facilitate improved lactate removal, which is similar to the effect of endurance training (42).

Blac responses have been shown to increase with progressively increasing intensity of muscular contraction (72,134). Due to pyruvate dehydrogenase's rate-limiting nature (135), this is to be expected. Anaerobic glycolysis meets energy requirements and subsequently produces pyruvate at a rate greater than pyruvate can be transported into the mitochondria and thus pyruvate and hydrogen ions will increase concentration in the cytosol. Lactate dehydrogenase acts to catalyze the reaction between the increasing concentrations of these products of anaerobic glycolysis to produce lactate. As RT to failure presents a maximal stimulus to both aerobic and anaerobic metabolism, it might be expected that blood lactate production is increased during exercise and, subsequently, stimulates the mechanisms involved with its removal and metabolism.

As discussed with other variables, intensity should be accurately defined and controlled for in experimentation. Such studies that have performed RT to a point of failure demonstrate significant increases in acute Blac (~ 6.5 to 17 mmol L^{-1}) (31,39,52,74,148). However, it is clear that the protocols used in these studies vary considerably (i.e., load, sets, repetitions, and range), which makes it difficult to analyze any one particular RT variable that is exerting an effect upon Blac accumulation except for intensity. Additionally, the study by Denton and Cronin (39) requires careful interpretation since they compared 3 different rest and loading schemes yet only one where participants performed exercise to a point of failure. Indeed, this was the only group to show significant increase in Blac.

Longer repetition durations may be of greater intensity than shorter durations (25). The difficulty interpreting the results of Hunter et al. (73) was highlighted in the section on VO_2 , which also applies to the Blac findings with results favoring the group that trained at greater intensity (the TT group) for demonstrating greater Blac accumulation. Gentil and colleagues (52) also examined Super-Slow (SS) training and concluded that it presents little in the way of metabolic stimulus. They compared 4 groups performing the leg extension exercise using a 10 RM. The first group performed repetitions at

a SS duration, the second group performed traditional repetitions, and the remaining 2 groups performed differing isometric holds at full extension. All groups except the SS group, completed repetitions to failure defined as "...when the subject was not able to completely extend the knees during two consecutive repetitions." The SS group performed a single standardized 60 sec repetition with 30 sec for eccentric and 30 sec for concentric phase, and as such there is no way of knowing whether it was to failure and, therefore, of maximum intensity. Their results indicate no differences between the groups performing exercise to failure, and only a significant difference between the isometric groups and the SS group.

Exercise that results in the accumulation of blood lactate at or above the lactate threshold (Tlac) produces a significant improvement in Tlac (38,47). As previously mentioned (31,39,74,148), RT produces relatively high concentrations of blood lactate (~ 6.5 to $17 \text{ mmol}\cdot\text{L}^{-1}$). It would appear that RT might be able to produce improvement in lactate clearance mechanisms. Yet, despite the intuitive plausibility of this hypothesis, more research in the form of controlled training intervention is needed to confirm it.

3.4 Molecular Responses

Molecular signaling pathways control many of the potentially stimulated adaptations. Recent reviews (11,32,85,105) further reinforce the dichotomy between RT and traditional CV adaptations. The argument that endurance adaptations are mutually exclusive to RT adaptations is specific to what Atherton et al. (10) have termed the AMPK-PKB switch. The adenosine monophosphate-activated protein kinase pathway (AMPK) plays an important role in: (a) inducing mitochondrial biogenesis (i.e., mitochondrial proliferation and up regulation of mitochondrial enzymes) (122,157); (b) stimulating slow twitch fiber phenotype transformation (91); and (c) inducing formation of oxidative properties in type IIx fibers (5). Thus, AMPK is held as the key instigator of endurance adaptations in skeletal muscle. Contrastingly, the mammalian target of rapamycin pathway (mTOR) induces a cascade of events leading to increased muscle protein synthesis (i.e., hypertrophy) (21, 22). Atherton et al. (10) examined the effect of two different electrical stimulation programs on rat muscle; a high frequency program that is proposed to mimic RT, and a low frequency program that is proposed to mimic endurance training. The results indicate that endurance type exercise favors AMPK activation and resistance type exercise favors mTOR activation. The two exercise types appear to be mutually exclusive. It is important to highlight that the reviews on this topic (11,32,85,105) conclude that endurance and resistance type exercises are distinctly different in their acute molecular signaling and chronic adaptations. Both draw heavily upon the AMPK-PKB switch described by Atherton et al. (10). However, it is very likely that these conclusions are quite tenuous when considering the methodological limitations of the study by Atherton et al. (10), particularly in regards to the non-human participants and poor replication of human training programs through electrical stimulation.

Other studies have also demonstrated AMPK as an inhibitor of mTOR activation. Hardie and Sakamoto (60) present a comprehensive review of this area. Then, too, further clarifying this relationship, Dreyer et al. (41) showed that during intense RT (10 sets of 10 repetitions at 70% 1 RM with the need to reduce the load for some participants in order to achieve 10 repetitions, which suggested that failure was achieved) in human subjects AMPK was significantly activated and mTOR was inhibited. This finding is in contrast to the suggestions based upon the study of Atherton et al. (10) that RT does not activate AMPK. Dreyer et al. (41) also reported that 1 to 2 hrs after RT upstream regulators of mTOR, such as protein kinase B (PKB; activation of PKB deactivates tuberous sclerosis complex 2, an inhibitor of downstream mTOR processes) and mTOR phosphorylation were significantly increased. This study suggests the potential of RT to elicit adaptations normally associated with endurance training. Research by Koopman et al. (84) further supports these findings where. They used a similar RT protocol. In addition, the acute effects of AMPK activation only inhibit

mTOR during exercise (21) while post-exercise transient up-regulation of mTOR upstream regulators occurs and a delayed increase of mTOR phosphorylation is observed (21,41).

Frosig et al. (51) examined AMPK activity in response to leg extension training. Although described as an endurance training protocol, the training was performed at 100% of peak workload in order to “...ensure recruitment of the majority of muscle fibers...” This could be considered intense RT based upon the definition of intensity used in this review. They also reported a significant increase in AMPK activity. The implication is that exercise of high enough intensity results in activation of the AMPK pathway regardless of the modality of the exercise (41,51). In agreement, Gibala et al. (54) have shown that AMPK is also activated during intense interval exercise. That AMPK is active independent of modality as long as intensity is high should not be surprising as AMPK is a key sensor of cellular energy requirements and responds most readily to increases in the cellular AMP:ATP ratio (59,60). During intense exercise, the AMP:ATP ratio is increased due to the increased rate of ATP use (72,128,136) and thus AMPK is activated. Recruitment of type IIx muscle fibers during RT to failure (30) produces greater depletion of ATP due to the fibers’ greater myosin ATPase activity (128). This is in agreement with the finding that AMPK activation is also the greatest in type IIx fibers after exercise (89). Resistance training to failure should result in activation of AMPK through these processes, as well as the subsequent delayed activation of mTOR, which presents a molecular mechanism by which RT can produce improvement in CV fitness, strength, and hypertrophy. Lastly, satellite cell activation through RT also induces mitochondrial gene shifting (147) that presumably would also control mitochondrial adaptation in response to RT.

3.5 Myocardial responses

The oxygen transport system and, therefore, VO_2 and its metabolic constituents have been discussed in part. However, as noted in the methods section, the oxygen transport system is also influenced by central CV variables. A discussion of the acute responses that might stimulate adaptation in the central CV variables is relevant to this review. For example, it is thought that the increased blood pressure responses with RT might be associated with the adaptation in cardiac dimensions (33). The adaptation might result in an improvement in maximal cardiac output and oxygen delivery.

Resistance training has previously been shown to be associated with an increase in systolic blood pressure (SBP) in the range of 270 to 480 mmHg (8,94,96). In general, studies demonstrate that RT significantly increases BP with a more pronounced effect on SBP (8,81). The effect on diastolic blood pressure (DBP) is less pronounced and, in some cases, unchanged or slightly decreased (8,81). Muscle contraction type also impacts the blood pressure response. Okamoto et al. (113) found that when load was set relative to 80% peak torque, concentric contractions resulted in a greater response in all CV variables measured than during eccentric contractions. This is not surprising since concentric contractions also elicit a higher VO_2 response (7) due to the required activation of more motor units to produce the same force output as an eccentric contraction (78). Similarly, Huggett et al. (71) showed that isometric contractions resulted in a greater hemodynamic response than eccentric contractions. Okamoto et al. (113) also demonstrated an increase in the hemodynamic variables that increase myocardial oxygen consumption as concentric exercise intensity is increased.

Blood pressure changes during exercise should be distinguished between responses that occur at the myocardial level and responses that occur at the peripheral vasculature level. Indeed, separate adaptive effects might result centrally and peripherally. This is because the increase in SBP during RT is secondary to the increased intrathoracic pressure associated with a valsalva maneuver (90,94), and the increased intrathoracic pressure that is transmitted directly to the arterial vasculature as increases in SBP (65). Thus, the pressure that the myocardium is ‘exposed’ to (i.e., left ventricular transmural pressure = left ventricular pressure – intrathoracic pressure) is not elevated above resting

values (26). This is further supported by Haykowsky et al. (63) who reported that while intrathoracic pressure increased significantly from 1.7 mmHg to 111.7 mmHg during a leg press exercise at 80% 1RM, there was no significant difference in left ventricular (LV) wall stress.

When central hemodynamic changes have been measured directly using right heart catheterization during RT, there is a significant decrease in peripheral vascular resistance and both an enhanced cardiac work index and left ventricular stroke work index (100). These responses are indicative of an increased coronary perfusion. Echocardiography also demonstrates that left ventricular function is maintained during RT in healthy subjects (82). As RT intensity increases, the rate of blood flow also increases linearly (3,46). Central hemodynamic responses to RT (i.e., no significant change in direct heart pressure) would appear in part to be due to the skeletal muscle pump enhancing venous return (140). Lack of skeletal muscle pump action may explain the increased hemodynamic response in isometric contractions (71). Coronary blood flow and perfusion may be augmented due to enhanced venous return (44), leading to enhanced left ventricular function during RT.

These findings appear to indicate that little acute stimulus exists to produce adaptation in myocardial dimension. However, heart rate (HR) is also significantly increased during RT (8,71,81,113). As with other physiological variables, it would appear that when intensity is controlled, HR increases linearly. Arent et al. (6) showed that when volume is controlled, an increase in load leading up to the subject performing exercise to failure results in a linear increase in HR and rating of perceived exertion (RPE). Increased stress to the myocardium through increased HR rate might possibly be a mechanism by which adaptation occurs. Alternatively, the volume of blood pumped by the heart is a possible mechanism for adaptation as well. Morganroth et al. (104) suggested that eccentric hypertrophy adaptation (i.e., proportional increase in ventricle chamber size and LV wall thickness) is a product of a high cardiac output while concentric hypertrophy characterized by an increased ratio of wall thickness to radius appears as a product of the volume of blood pumped, which might be greater in the potentially high volume workouts often preferred by bodybuilders as opposed to potentially higher load sessions by weight lifters. In agreement, Haykowsky et al. (64) reported that concentric hypertrophy is associated with Olympic weightlifters while eccentric hypertrophy is associated with bodybuilders. Although this is speculation based on an association, it will be discussed in the subsequent section on myocardial adaptations to RT.

3.6 Vascular response

Increased cardiac output enhances oxygen transport while local blood supply to the muscle directly impacts oxygen delivery. Therefore, the acute stimulation of the peripheral vasculature might result in enhanced local oxygen supply. Brown (24) suggested that the primary acute stimuli determining vascular remodeling adaptations are the shear stress and wall tension of the vasculature. As explained, with increased RT intensity, the rate of blood flow is increased linearly (3,46). Tinken et al. (150) reported that shear rate was significantly increased in response to the handgrip RT exercise. An increase in blood flow and consequently in shear stress due to RT may provide the stimulus for endothelial adaptation in nitric oxide production (a potent vasodilator that may serve to enhance local blood flow). Shen and colleagues (132) identified shear stress as the primary stimulus for production in nitric oxide by the endothelium. They also commented that brief exercise may up-regulate gene expression for the enzyme responsible for its production. There is, however, a lack of data testing this hypothesis in humans. Long term endurance training beginning at low-intensity has been shown to be ineffective in altering plasma nitrate/nitrite levels (23). However, there may be some training effect in vasodilatory response as shown by the greater magnitude in blunting of cold induced vasoconstriction in competitive cyclists when compared to sedentary controls while performing leg extension or handgrip exercise (156). In addition, Wray et al. (156) showed that vascular conductance in response to maximal exercise to fatigue was significantly increased in both sedentary and endurance trained

subjects, but with a greater response in subjects who were endurance trained. It is important that more research is carried out to identify whether this response also occurs in humans as a result of RT to failure. DeVan and colleagues (40) demonstrated a decrease in arterial compliance, which would enhance blood flow, following RT to failure. However, the decrease lasted <60 min after completion of the exercise. In light of this point and the contraction intensity dependent increase in blood flow (3,46), further research should examine whether adaptations in the vasculature due to RT to failure are indeed mediated by this mechanism.

4. SUMMARY OF PART 1: ACUTE RESPONSES TO RT

As evidenced herein, the acute metabolic and molecular responses to RT performed to failure appear not to differ from traditional endurance or aerobic training when intensity is appropriately controlled. Acute myocardial function appears to be maintained and, perhaps, enhanced in response to acute intense RT with little stimulus occurring in terms of pressure and only an increased contraction rate (i.e., HR and potential stimulus from volume of blood pumped). The magnitude of acute local blood flow response appears to be determined by the contraction intensity. Meanwhile, there is a lack of data with human subjects demonstrating the effect upon other vascular factors such as endothelial stimulation of nitric oxide production. Figure 1 presents a schematic depicting the acute responses of RT to failure. More research is necessary in several areas to help further evaluate the effect of RT on acute variables. However, an understanding of the acute responses to intense RT helps to identify and discuss the chronic adaptations that may occur in CV endurance.

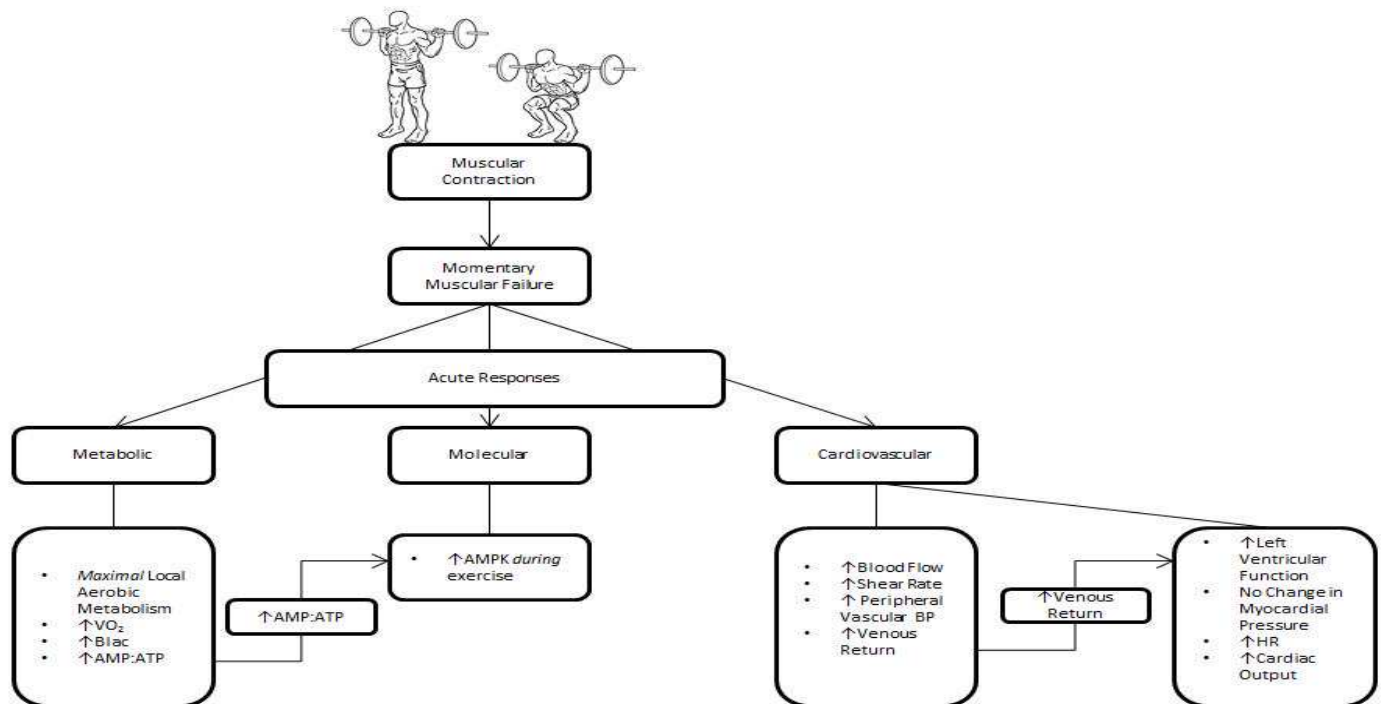


Figure 1. Schematic of the acute physiological responses to RT performed to momentary muscular failure.

5. PART 2: CHRONIC ADAPTATIONS TO RT

5.1 Metabolic and Molecular Adaptations

Various adaptations (including oxidative enzyme, muscle fiber phenotype, and mitochondrial biogenesis) are observed in the peripheral musculature that may explain the improvement in CV endurance in response to RT. Resistance training is shown to increase resting muscular ATP

concentration (97), which suggests that the aerobic ATP production is improved. However, this finding is not an absolute certainty purely from the results presented by this study (97). Other evidence examining RT interventions demonstrates that markers of aerobic metabolism are increased through RT. This would support the conclusion that mitochondrial ATP production is enhanced. For example, Jubrias et al. (79) compared a group performing RT, a group performing traditional endurance training, and a control group. The researchers reported an increase in muscle maximal oxidative phosphorylation capacity following RT (57%) in the elderly an increase that was comparatively greater than the group performing endurance training (31%). The intensity of the RT was not controlled (10-15 repetitions at 60-70% 1RM proceeding to 4-8 repetitions at 70-85% 1RM varying 3-5 sets), which, although may have involved a reasonably high degree of effort considering repetition ranges at similar loads (70, 133) is not consistent with the definition in this review. Frontera and colleagues (50) reported an increased mitochondrial enzyme activity (citrate synthase) in older subjects as a result of RT. Again, a specific definition of the RT's intensity is impossible since the subjects did not perform RT to failure (3 sets of 8 repetitions at 80% 1RM). However, Tang et al. (145) demonstrated an increase in oxidative potential in untrained men who performed RT to failure. They reported that RT induced significant improvement in both glucose phosphorylation enzymes (hexokinase) and aerobic enzymes involved in the citric acid cycle (citrate synthase and β -HAD).

It has been suggested that RT may serve to reduce mitochondrial density (86,93,95,125,149). Therefore, it may seem counterintuitive to find that RT increases mitochondrial ATP production and oxidative capacity. However, all but one of the studies cited failed to consider the concomitant increase in myofibrillar volume, (i.e., hypertrophy), when measuring mitochondrial density. Luthi et al. (93) found that absolute mitochondrial volume when accounting for myofibrillar increase (i.e., cross sectional area [CSA]) was unchanged following RT. Interestingly, Jubrias et al. (79) reported in their study that only the RT group demonstrated an increase in mitochondrial volume as measured by magnetic resonance spectroscopy, despite also being the only group to exhibit an increase in muscle CSA. Thus, it seems that at the least RT does not affect mitochondrial volume when hypertrophy is considered and may increase it. Since AMPK has been shown to induce mitochondrial biogenesis (122,157), which is clearly facilitated by intense RT, this may be the factor that is responsible for the mitochondrial adaptation (including the up-regulation of mitochondrial enzymes and mitochondrial proliferation).

Increase in oxidative capacity through RT may further be due to change in muscle fiber phenotype. Walker et al. (152) have suggested that an increase in oxidative mechanical power from RT may be due to the increase in type IIa fiber activity. A type IIa fiber phenotype confers greater oxidative capacity than that of type IIx and this has been suggested to explain improvement in aerobic capacity through RT (111). Staron et al. (137) found that weight lifters have a larger percentage of type IIa fibers compared to the controls, while the control group have a higher proportion of type IIx fibers. This may seem peculiar as the size principle would dictate that intense RT should recruit type IIx fibers and, therefore, stimulate the fibers to increase (30). However, intervention studies confirm that RT performed to failure induces a shift toward a type IIa phenotype (1,57,138,155). Adams et al. (1) demonstrated a significant reduction in type IIx fibers and concomitant increase in type IIa fibers, although there is no change in type I after RT to failure. Staron et al. (138) demonstrated a similar reduction in type IIx fibers and an increase in both type IIa and type I fibers in the vastus lateralis after the subjects performed lower body RT to failure. Willoughby and Pelsue (155) showed that 8 weeks of intense RT induced up-regulation in gene expression of type I and type IIa fibers and down-regulation of type IIx fiber gene expression. This shift has also been reported in older populations (58,87,131).

The adaptations that result from RT appear in part to be the result of activating AMPK when training is performed at a high intensity (41,51). The AMPK activation explains the observed increase in mitochondrial enzymes and proliferation. Also, the shift from type IIx to type IIa phenotype may further be explained by this as type IIx fibers exhibit the greatest activation of AMPK (89). Thus, it would not be surprising that the greatest adaptation should occur within them as AMPK activation in type IIx fibers may initiate the mitochondrial changes that result in the change towards a type IIa phenotype.

The adaptations described (up-regulation of mitochondrial enzymes, increased mitochondrial volume, and conversion to a type IIa phenotype) have been attributed to enhanced CV fitness (109). Therefore, it should be expected that an adaptation in such factors due to RT would also result in concomitant increase in CV fitness variables as has been clearly evidenced to occur.

5.2 Myocardial Adaptations

It is reasonable to expect that stimulation of the myocardium and peripheral vasculature might impart central adaptations to the oxygen transport system and, therefore, confer further improvement to CV fitness. As highlighted earlier, RT has been shown to be associated with an increase in SBP (270 to 480 mmHg) (8,94,96), and it is thought that the increase in pressure can be a stimulus to alter the left ventricular (LV) size (33). If it is, then, it should enhance pumping mechanics, total heart volume, and maximum cardiac output; all are thought to influence CV fitness (126,139). But, as mentioned in this review, the pressure may not be directly experienced by the heart itself (90,94).

While Pellicia et al. (115) reported that the values recorded for the 100 athletes did not exceed the upper limits of the normal range, Baggish et al. (12) suggested that persons performing RT over a 90 day period experienced LV hypertrophy. Similarly, Pellicia et al. (115) found significantly greater values for LV wall thickness in power athletes than in sedentary controls matched for age and body surface area. Pluim et al. (120) reported in a meta-analysis that a significant difference existed in the LV wall thickness between control (0.36 mm) and endurance-trained athletes (0.39 mm) as well as between endurance- (0.39 mm) and strength-trained (0.44 mm) athletes. Of course it is important to remember that these cross sectional data do not prove a causal relationship. Persons might have selected their sport based on their ability as a result of cardiac differences rather than chronic cardiac adaptations as a result of performing their sport.

A review of the effect of RT on cardiac hypertrophy suggested that RT does not always result in changes to LV geometry, including an increase in LV hypertrophy (64). Stating that the data are far from conclusive that RT of any kind will result in these changes, Haykowsky et al. (64) reported that 40% of all resistance-trained athletes have normal LV geometry. Their review considered the type of RT (bodybuilding vs. weight-lifting routines) as well as the age factors and the effects of steroid use. They suggested that weight-lifting techniques appear to produce the most significant changes in LV mass (concentric hypertrophy) while bodybuilding appears to produce eccentric hypertrophy. Unfortunately, these studies did not detail or control the intricacies or intensity of the training regimes (12,115).

In essence, then, the myocardial adaptations from different exercise stressors without consideration of the genetic influence or the use of anabolic steroids are still unclear. Many authors state that concentric LV hypertrophy is not a product of RT alone (151). Indeed, the literature provides no clear evidence to suggest that RT of any kind will present a stimulus sufficient to induce structural myocardial adaptations. However, the studies that have attempted to examine this variable are generally poorly controlled with regards to the RT variables (especially intensity). Future research should examine myocardial adaptations, including the control for steroid use.

5.3 Vascular Adaptations

In regards to the vascular adaptations proposed to enhance local muscular blood flow and oxygen supply, shear stress is likely one of the acute stimuli for inducing vascular adaptations. Research by Tinken et al. (150), in addition to examining acute responses, also examined adaptation to the hand grip contraction RT protocol, reported an increase in flow mediated dilation and brachial artery peak reactive hyperemia (an index of resistance artery remodeling).

Having observed that older males who participated in RT had significantly greater whole leg blood flow and conductance than sedentary controls, Miyachi et al. (103) suggested that RT may favorably influence blood flow. However, their study was a cross sectional observation. It may be expected that improvements in vascular blood flow and compliance due to any exercise may be limited to those aging or with vascular disease since the majority of research has focused upon these populations. On the other hand, Tanimoto et al. (146) demonstrated a significant increase in femoral blood flow in healthy young males after 13 wks of RT to failure. They used two groups, either performing exercise with a low load and long repetition duration (LST; ~55% to 60% 1RM, 3 sec concentric and 3 sec eccentric) or a high load and short repetition duration (HN; ~85% to 90% 1RM, 1 sec concentric, 1 sec eccentric). Both LST and HN significantly increased femoral blood flow (18% and 35%, respectively) with no significant difference between groups. There may have been an effect of load due to the greater increase in the HN group, but this is not clear and future research attempting to replicate this result would help clarify if there is indeed a difference. It is clear that RT to failure produces vascular adaptations in healthy young males. In support of the conclusions by Miyachi et al. (103), and in addition to the findings by Tanimoto et al. (146), Anton et al. (4) demonstrated significant improvement in femoral blood flow (55% to 60%) in older males and females after 13 wks of RT to failure. These changes were independent of changes in vasoconstrictors such as endothelin-1 and angiotensin-II, and there was no change in the arterial wall thickness. Rakobowchuk et al. (121) demonstrated improved endothelial function through increased peak flow and brachial artery diameter independent of flow-mediated dilation after RT to failure. These results appear to support the notion that enhanced vascular function may predominantly be a result of adaptation at the arteriolar level.

Brown (24) stated that capillary proliferation and 'arteriolarization' are an integral response to coronary vascular remodeling, and the same may be applicable to peripheral vascular remodeling. Green et al. (57) found increased capillary contacts as a result of 12 wks of RT to failure. Additionally, Hepple and colleagues (67) showed that older men performing RT to failure over a 9-wk period significantly increased both capillary contacts and capillary to fiber ratio. The same changes took 18 wks to reach significance when performing just aerobic training. Aerobic training intensity was not reported, but it seems reasonable to suggest it was likely significantly less than RT intensity unless also performed to exhaustion. Given that the only quantifiable measure of exercise intensity is momentary muscular failure and traditional aerobic training is not generally performed in this manner, then, this may account for the faster adaptations in the RT group. Harris (61) commented that endurance exercise positively affects capillary changes, but there are conflicting data on RT. Also highlighted was that training intensity may be an important factor, which is supported by the data from Hepple et al. (67).

It should also be noted that studies have reported that intense RT does not improve capillary density (67,153). However, both studies cited here also showed an increase in muscle CSA after training. In the same manner that CSA increases confound measures of mitochondrial density, it is likely to affect capillary density measurements. In contrast, Hagerman et al. (2000) showed both increased muscle CSA and increased capillarization after RT to failure. The data of Hepple et al. (67) and Green et al. (57), which identified capillary contacts and capillary to fiber ratio, are also probably more indicative

of the vascular remodeling in response to RT (since the measures are not confounded by concomitant CSA increases). Thus, it seems that significant vascular remodeling occurs at the peripheral local muscular level as a result of RT to failure which may enhance local oxygen supply.

6. SUMMARY PART 2: CHRONIC ADAPTATIONS TO RT

A plethora of research demonstrates the positive physiological adaptations that may mediate the observed improvement in CV fitness as a result of RT. It is also clear that these adaptations are, for the most part, a result of RT at high intensity (i.e., performed to failure). Adaptations including, up-regulation of mitochondrial enzymes, mitochondrial proliferation and conversion towards a type IIa phenotype may be the physiological adaptations underlying observed improvement in CV fitness variables. There is little evidence to support the contention that the myocardium is directly stimulated, and that any subsequent adaptations are promoted within it as a response to intense RT and so it seems unlikely that this is a mechanism involved in improving CV fitness as a result of RT. However, vascular adaptations, including capillarization, have been shown to occur within the peripheral musculature as a response to RT to failure. They are likely to contribute to the improvement in CV fitness through enhanced local muscular oxygen supply. Figure 2 presents a schematic depiction of the chronic adaptations produced by RT performed to failure. It would appear that such adaptations are not dependent upon a particular exercise modality as similar adaptations have been evidence through other forms of intense training and comparative studies of differing modalities do not clearly favor one form over another. We suggest that the key factor in determining physiological adaptations to promote CV fitness is intense muscular contraction.

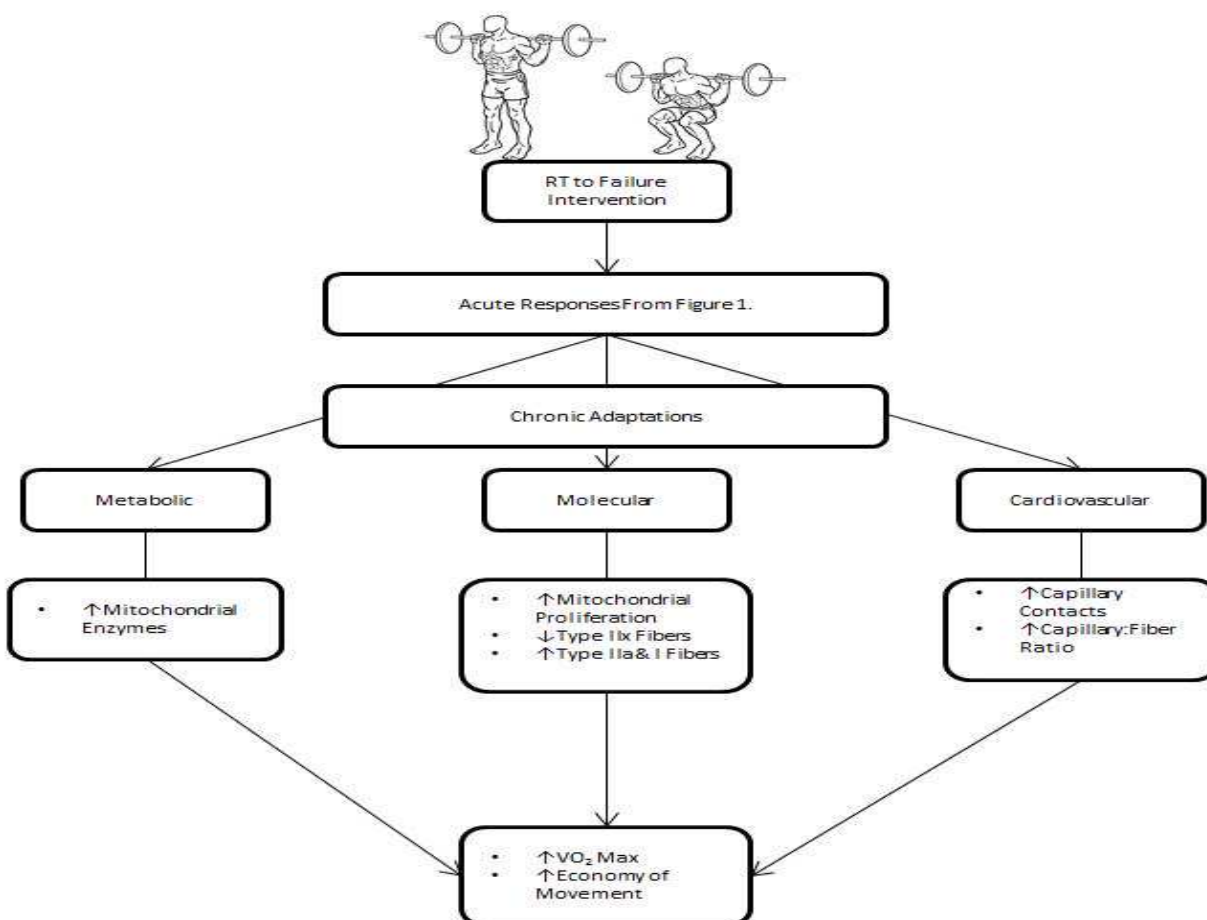


Figure 2. Schematic depiction of the chronic physiological adaptations and improvements in CV from RT performed to momentary muscular failure.

7. CONCLUSIONS

7.1 Areas of Future Research

Throughout this review areas where research is inconclusive or absent have been highlighted. Areas for future research include: (a) Improvements in \dot{V}_{IAC} have only thus far been evidenced in untrained populations through one study and so further studies are needed to clarify this response; (b) Although the whole body $\dot{V}O_2$ response to exercise may bear little impact upon the CV adaptations, further studies examining $\dot{V}O_2$ during RT (without averaging to included non-exercise periods) to failure may elucidate the role of local active muscle $\dot{V}O_2$ in CV adaptations; (c) Also, considering the role of intensity and that longer repetition durations may be of greater intensity than shorter durations, it is also of interest to examine the effect of this variable upon $\dot{V}O_2$ during RT; (d) Further research identifying the stimulus responsible for vascular adaptation (i.e., capillarization) is also of interest, as well as the role of endothelial nitric oxide production and vascular compliance in response to RT; and (e) In reference to central CV adaptations, future studies examining controlled RT interventions in populations controlled for steroid use may also be of use in clarifying whether RT to failure results in myocardial adaptations.

7.2 Practical Applications

In light of this review, several practical applications should be noted. While it has been shown that the physiological adaptations that promote CV fitness are similar between traditional aerobic endurance exercise and RT modalities, the comparative studies that have controlled RT intensity suggest no significant differences. The extent of physiological responses may differ in different populations. For example, trained athletes show little improvement in $\dot{V}O_2$ max in response to RT, which is likely a function of their level of trainability. Therefore, the value of RT may differ with respect to the population considered. It is very likely that people who are either untrained or not involved in organized sporting competition, but who have the desire to improve their CV fitness may find value in RT performed to failure. In fact, this review suggests that RT to failure can produce CV fitness effects while simultaneously producing improvements in strength, power, and other health and fitness variables (48). This would present an efficient investment of time as the person would not have to perform several independent training programs for differing aspects of fitness. Contrastingly, the value of RT in improving an athlete's CV and potentially sporting performance may be less. Although the physiological adaptations produced would be similar should the athlete perform RT, participation in other modalities of training may be essential to ensure that the specific motor skills and other variables involved with their performance are also trained. It is beyond the scope of this review to suggest optimal means of employing RT (i.e., load, set volume, and/or frequency) in order to improve CV fitness since there are no published studies on this topic. Therefore, it is recommended for athletes and non-athletes, whether traditional or circuit style, that RT should be performed to failure as recommended by Fisher et al. (48) to improve CV fitness.

7.3 Conclusion

Resistance training performed to failure can induce acute and chronic physiological effects which appear to be similar to aerobic endurance training, which in turn produces similar enhancements in CV fitness. A limited number of direct comparison studies of the two modalities has been conducted. The studies that have been appropriately controlled are suggestive of no significant differences in CV or physiological responses. This review has also highlighted areas where current research is inconclusive. Therefore, it is important that future research is carried out to understand the role of RT to failure in setting the stage for increased CV fitness. We are optimistic and encouraged that this review will help to promote a paradigm shift in this area of training and research. Identifying a particular modality of exercise as being 'aerobic' or 'CV' constitutes a misnomer. The extent that any modality of exercise produces CV fitness adaptations appears to be dependent primarily upon the

intensity of the exercise. Chronic adaptations appear to reside predominantly at the peripheral muscular and vascular level. Indeed, we are not the first to consider this false dichotomy between RT and aerobic training (119). Phillips and Winnett (119) have questioned the RT/aerobic dichotomy with regard to health outcomes. They, too, suggest that reconsideration of the value of RT is important. We hope that this review will encourage researchers and practitioners to consider the implications in the design and interpretation of future research as well as when prescribing exercise for the purpose of improving CV fitness. Thus, in conclusion, we contend that performance of RT to failure will produce significant improvement in CV fitness that occurs through physiological adaptations such as up-regulation of mitochondrial enzymes, mitochondrial proliferation, conversion towards a type IIa phenotype, and capillarization.

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